Chemical Looping Gasification for Sustainable Production of Biofuels

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Deliverable D7.5:

Strategies for biofuel deployment based on residuals

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Author(s): [1]Nadine Gürer, [1]Reinhard Haas

Affiliation: [1]Technical University of Vienna (VUT)

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1 Introduction & Objective

1.1 Introduction

In light of the European Green Deal's target to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels and to render Europe the world's first climate-neutral continent by 2050 [13, 14, 15 & 19], it is crucial to increase the market share of biofuels in the European energy and transport sector. With regards to biofuels as final energy carriers, however, it is also important to distinguish between their different categories (BF-1, BF-2 and BF-3) and corresponding maturity levels. While first generation fuels have the advantage of being produced by an already fully mature technology, this is presently not entirely applicable for second generation biofuels (e.g. Fischer Tropsch (FT) Diesel) and not at all for third generation fuels. As first generation biofuels have been associated with inefficiencies such as high cost, low net energy yields, as well as potential land use changes and competition to food production, second generation biofuels have been considered as a promising way to render biofuels cleaner [7]. This deliverable aims to make use of recent data on selected biomass-to-FT-Diesel chains from the EU Horizon 2020 CLARA project[1] to analyze and compare the ecological and economic performance of selected biomass-to-FT diesel chains to previous literature.

1.2 Objectives of WP7: an overview

Prior to introducing the specific objectives of Task 7.5, the overall objectives of Work Package 7, which consists of a total of five sub-tasks (T7.1 – T7.5), are summarized below:

- Estimate the costs for feedstock supply, gasification, and fuel synthesis plants,
- Evaluate the energetic, economic, environmental, and socio-economic performance of the considered biomass-to-end-use chains under different framework conditions,
- Confirm that biomass feedstock chosen are best suited for biofuel production from a technological, economic, and environmental point of view,
- Characterise potential biomass residues and evaluate the solutions to provide high availability for biomass-to-end-use chains in different countries involved,
- Comparative assessments of the economic performance, social and environmental aspects of possible full scale process plants, and supply chain setups and their replication potentials.

1.3 Objectives of Task 7.5: Modelling of potential socio-economic impacts and market diffusion

More specifically, it is foreseen that Task 7.5 fulfils the following objectives:

- Calculate overall costs and GHG-emissions of relevant constellations of the defined chain links under different boundary conditions by using a refined database including the information gathered from the other tasks of WP7 **(1)**,
- Estimate the socio-economic and ecological viabilities of the examined constellations by comparison with costs, emissions, and jobs created from competitive biomass deployment for energetic and non-energetic use as well as from reference fossil fuel products **(2),**

[1] This work has received funding of the European Union's Horizon 2020-Research and Innovation Framework Programme under grant agreement No. 817841 (Chemical Looping gasification foR sustainAble production of biofuels-CLARA).

- Develop scenarios up to 2050, using Technological Learning approaches and, based on sensitivity analysis of these technology diffusion scenarios, drawing recommendations for policy makers and stakeholders about socio-economic and environmentally sound deployment strategies of bioenergy carriers based on chemical looping gasification of biogenic residues.**(3)**

1.4 Notes on Approach and Structure of Task 7.5

The research and overall effort undertaken with respect to Task 7.5 can be divided into two sub-sections: the first being a preliminary literature research and conceptualization of a generic biomass-to-liquid fuel chain and the second one being the development of a method of approach for objectives 1 to 3. This is reflected in the structure of the rest of this document, which will start with a summary of the preliminary literature research and the generic biomass-to-liquid fuel chain that was conceptualized. In a second step, the methods of approach, together with all relevant parameters and equations related to the analysis of objectives 1 to 3, will be introduced. In a final step, the results will be analysed and interpreted to form concrete recommendations and arrive at relevant conclusions for the successful deployment of biofuels. On a final note, it should be mentioned that, in order to avoid the repetition of aspects of the biomass-to-biofuel chain analysis that have been fully or partially completed in previous tasks related to WP 7, some aspects of objectives 1 to 3 will be handled in less detail, whereas some other aspects of the analysis that provide uniquely new insights and explicitly represent an added value in relation to what has already been done, will be pointed out more eminently.

2 Preliminary Literature Research and Conceptualization of a Generic Biomass-to-Liquid Fuel Chain

2.1 Relevant Key Performance Indicators (KPIs)

As a first step, before starting the literature survey on components of the BtL fuel chains under study, the key performance indicators (KPIs) defined by the CLARA consortium at the onset of the project (6 in total) have been examined and those that are explicitly relevant to T7.5 have been summarized in **Table 1** below.

Table 1: KPIs relevant to Task 7.5, as defined by CLARA consortium [1].

KPI	Definition	Target	Means of verification
Fuel cost	Cost for production of transport fuel considering revenues from sale of power, heat, CO_2 and others	< 0.7 €/l	Techno-economic assessment of entire BtL chain
CO_2 efficiency	Net emissions of CO_2 per produced fuel considering CO_2 storage	< 0	Life cycle analysis of entire BtL chain

2.2 Generic Biomass-to-Liquid Fuel Chain

As a second step, a generic Biomass-to-Liquid (BtL) chain featuring the main components relevant to the CLARA process has been developed and can be seen in **Figure 1** below.

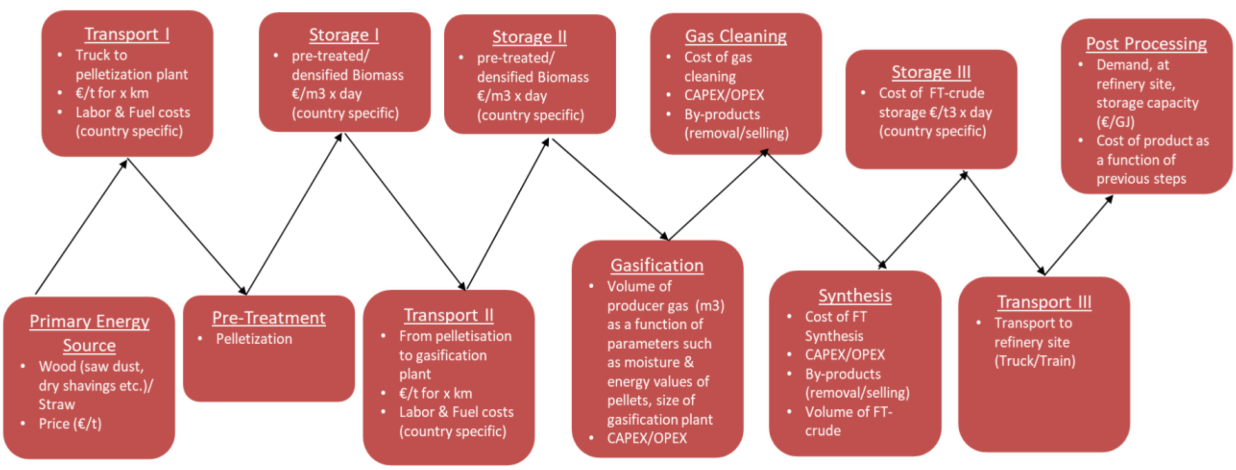

Figure 1: Generic Biomass-to-Liquid fuel chain for CLARA process

Identifying the main components of the CLARA process chain guided the preliminary literature survey that has been carried out in the first part of Task 7.5 and also framed the socio-economic analysis that was carried out in the second part of the task.

2.3 Selected Data from Literature for each BtL fuel chain component

After having narrowed down and identified the specific components of the CLARA process chain beginning from the primary energy source and ending at the refinery site, a literature survey has been undertaken to collect data for each step seen in **Figure 1**, at the European level. The aim of the literature survey was to gain a general understanding of the costs related to the individual steps of the CLARA process chain in comparison to previously reported, similar Biomass-to-Biofuel conversion processes. This also served to identify particular cost-intensive steps, as well as acting as a basis for further analysis of the process chain. In a final step, the overall cost of the Biofuel product as a function of all previous steps was "calculated", based on values found in literature. It should be noted that this is only a rough estimate at best, as ensuring a homogeneity in terms of countries (although all within the EU), as well as the years for which the values were reported, for all steps throughout the process chain represented a challenge. *Selected* data for *selected* steps of the BtL fuel chain above and corresponding literature sources have been summarized below for a wood residue-to-Biofuel case, in **Tables 2 & 3**.

In a second step, the literature survey above has been complemented by undertaking a comparison of total pellet production costs for selected biomass fractions. Selected data for the production of wood pellets within the EU has been summarized in **Table 2** below.

Table 2: Selected literature data for total pellet production costs

Country	Production cost, *wood pellets*
Austria	136, 6 €/t [6]
Sweden	135 €/t [3]
Germany	170 €/t [3]
Finland	124 €/t [3]

As a final step of the literature survey, the total production costs for selected BtL fuel chains have been visualized graphically, depicting overall production costs for 1 and 20 MW scale plants, as well as the costs of each individual step of the generic BtL fuel chain depicted in **Figure 1**. This was done in order to facilitate any inferences related to e.g. particularly cost-intensive steps, as well as to better depict the relationship between overall production costs and plant size (economies of scale). The visual depiction of a wood residue-to-liquid biofuel chain can be seen below, as **Figure 2**.

Table 3: Selected Literature Data for Generic Biomass-to-Liquid fuel chain for CLARA process

Primary Energy Source	Transport I	Storage I[2,3]	Transport II	Storage II
• Wood residues, AT: 30-60 €/t [2] • Sawmill products, AT: 20-40 €/t [2] • Industrial residues, Finland: 95 €/t [3] • Sawdust (oven dry), Finland: 90 €/t [3] • Dry wood residues (max. 10% moisture), Norway: 110 €/t [3] • Wet sawdust, Norway: 90 €/t • Dry wood shavings, Sweden: 95-115 €/t [3] • Wet sawdust, Sweden: 85-100 €/t [3]	•Wood chips via truck to pelletisation plant, AT (~21 km): 0,9 €/ GJ [4] •Transportation costs for ~50km (oven dry residues), Finland: 20€/t (1.1 €/ GJ) [3]	•6 months (small terminal): ○ for 5000 m^3 of wood pellets stored: 2,77 €/m^3 [5] ○ for 30000 m^3 of wood pellets stored: 2,44 €/m^3 [5] •6 months (large terminal): ○ for 50000 m^3 of wood pellets stored: 2,86 €/m^3 [5] ○ for 100000 m^3 wood pellets stored: 2,52 €/m^3 [5] •3 months: ○ for 5000 m^3 stored: 2,40 €/m^3 [5] ○ for 10000 m3 stored: 2,2 €/m^3 [5] ○ for 30000 stored: 2,07 €/m^3 [5]	Domestic transport, standard wood pellets, Sweden: 12 €/t [3]	*similar to storage 1*

2 for wood residues this depends on the time (t) material is stored and m^3 of material (€/m^3)

3 Values for AT

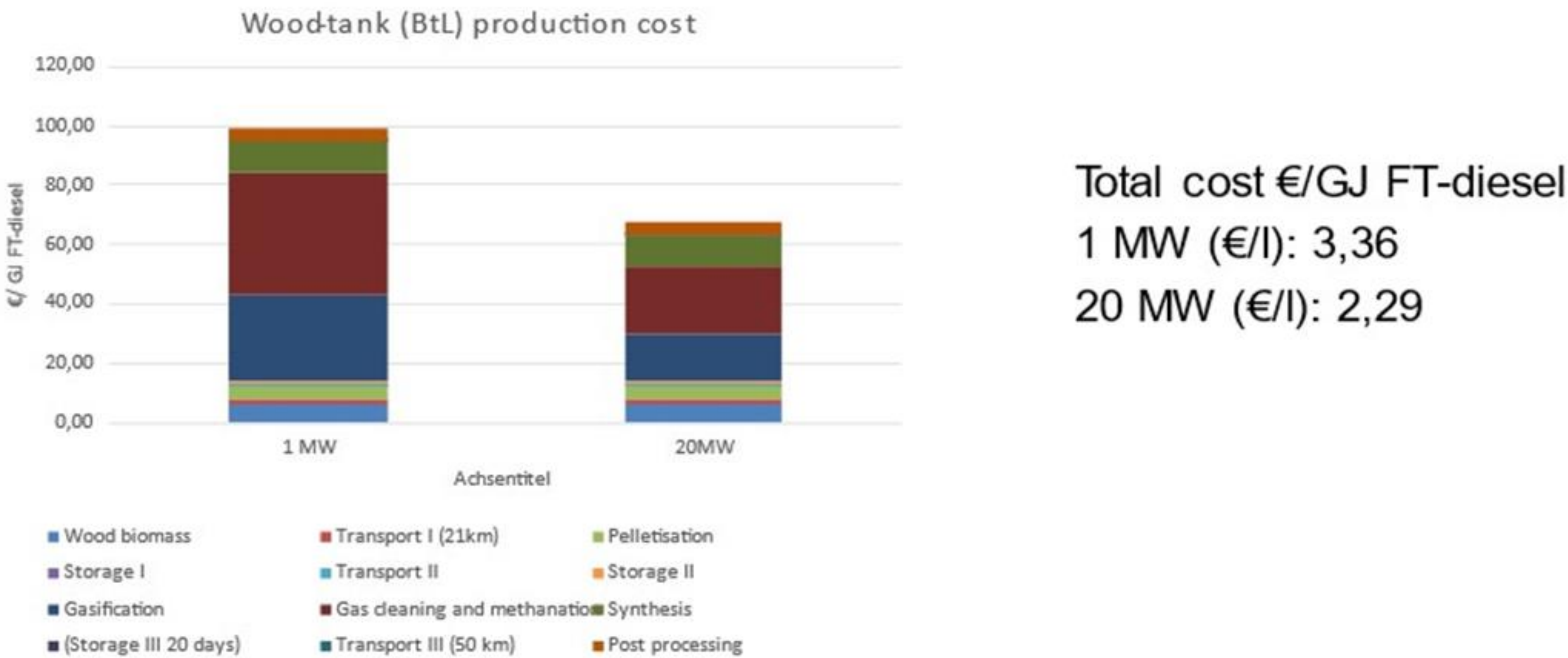

Figure 2: Total production cost for wood-residue-liquid Biofuel chain

Based on the preliminary literature survey that has been undertaken prior to the analysis carried out for this task, a total production cost of 3,36 €/l for a 1 MW plant and a total production cost of 2,29 €/l for a 20 MW plant have been estimated. While the plant under study throughout the CLARA project operates at a 200 MW scale (this has been taken into consideration for the second part of the analysis of this task), the two representative scales of 1 MW and 20 MW have been chosen to demonstrate the expected economies of scale effect, which is expected to continue with rising operating capacities. A second aspect that was closer analysed is the cost distribution among the individual BtL fuel chain components: as evident from **Figure 2** above, the most cost intensive steps have been reported to be the gasification and gas cleaning steps, while transportation and storage steps have been reported to be generally low-cost by comparison. It is worth mentioning, that the chemical looping gasification technique which is being analysed by the CLARA project is a novel technique and thus is not yet well documented in literature – the values of the preliminary literature research are thus generally based on regular biomass gasification processes. Another point worth mentioning is, that one of main advantages of the novel CLG technique is that it is expected to reduce the costs of the gasification and syngas treatment/ cleaning steps, justifying further research on and investment into this novel technique, as it addresses the most cost-intensive steps of the BtL fuel process chain. Finally, it should be noted that the above overall production costs and costs for the individual process steps are a rough estimate based on varying years and countries for regular biomass gasification for the production of biofuels at a lower plant scale and thus does not represent the findings or technology of the CLARA project. A higher price estimate of 2,29 €/l for a 20 MW plant is therefore not to be taken as a comparison to the CLARA project's KPI of 0,7 €/l for a ~200 MW CLG plant.

3 Environmental & Economic Assessment

As foreseen in the objectives of Task 7.5, an economic and environmental assessment of the selected BtL fuel chains was carried out. However, it should be noted that, in order to avoid repetitions with respect to the analysis that has been carried out in previous tasks related to WP7 (particularly Task 7.2 – Tasks 7.4, which analyzed e.g. the cost of the gasification and fuel synthesis plants and carried out a techno-economic evaluation as well as a life-cycle analysis), a methodology for the environmental and economic assessment will be briefly described together with relevant parameters and equations, followed by an evaluation of the two particular cases under study in the CLARA project.

3.1 Definition of relevant parameters & equations

For the economic analysis energy costs, capital costs, as well as the following other costs: transport, operation & maintenance (O&M), labour, electricity and heat are considered. The sum of these variables represent the total costs, C_{total}, for the production of a certain biofuel (BF) from a selected feedstock (FS) for a specific year.

$C_{total} = C_{energy} + IC.\alpha + C_{other}$ [€/ tonne FS] (1)

where:

C_{energy}……energy costs [€/tonne FS]

IC……investment costs [€/tonne FS]

α……..capital recovery factor

C_{other}…..∑transport, O&M, labour, electricity, heat [€/ tonne FS]

For the environmental analysis, the CO_2 input and the conversion efficiency for the selected feedstock, as well as the CO_2 input of the final biofuel product are considered.

Total specific CO_2 (BF, FS) = $\eta_{feedstock}$. CO_2 input $_{feedstock}$ + CO_2 input $_{biofuel}$ (2)

where:

$\eta_{feedstock}$……FS conversion efficiency

CO_2 input $_{feedstock}$……∑CO_2 (passive/sink, fertilizer, $fuel_{feedstock}$, $fuel_{transport}$) [kg CO_2/ kg FS]

CO_2 input $_{biofuel}$……∑CO_2 ($credit_{by\text{-}products}$, pressing, BF conversion, other WTT, $transport_{fill.\ stat.}$, TTW) [kg CO_2/kg BF]

Abbreviations: WTT… well-to-tank, TTW…tank-to-wheel

3.2 Pine Forest Residue pellets & Wheat straw pellets - to - FT - Diesel Chains

For the economic assessment of pine forest residue-to-FT diesel and wheat straw-to-FT diesel chains, the total production costs for each biomass-to-fuel chain was calculated as outlined in the method of approach, above. Data, such as e.g. feedstock costs (€/ ton FS), was taken from previously completed tasks within the CLARA project.

Figure 3 describes the structure of the total production cost (for the year 2020) of pine forest residues-to-FT diesel and wheat straw-to-FT diesel and compares these with the corresponding total production cost for conventional diesel for the selected year 2020 (€/kWh). The overall production costs are segmented into energy costs (orange), capital costs (grey) and other costs (yellow), while light blue denotes carbon tax/credits (in case of FT Diesel this is deducted and in case of conventional Diesel this is added onto the overall production costs): The green bars represent the overall production costs of both cases, with the carbon tax deducted. The advantages of CO_2 tax can be seen in its contribution to a decrease of the total costs / kWh of fuel for both biomass-to-FT diesel chains. Interestingly, the costs of production of FT diesel from wheat straw and those for conventional diesel in 2020 seem to be approximately equal when including CO_2 tax. This can be attributed partially to the lower than expected feedstock prices for wheat straw than was forecasted previously in literature, as in e.g. Ajanovic et al. 2012 [7]. According data from the CLARA project those were 36 €/ ton for wheat straw, which is significantly lower than the straw prices of 119 €/ton for 2020 assumed by Ajanovic et al. 2012 [7].

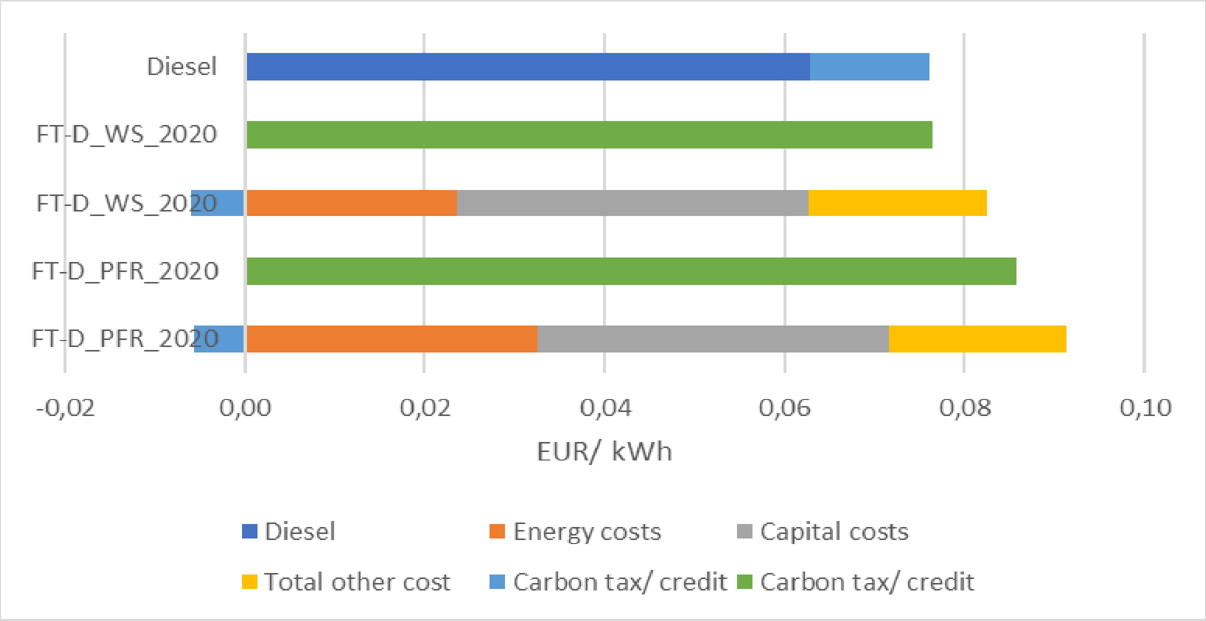

Figure 3: Segmented total production costs for wheat straw-to-FT diesel & pine forest residues-to-FT diesel chains incl. CO_2 taxes for 2020 compared to corresponding Diesel price (€/kWh) for the EU[4]

[4] Where FT-D_S and FT-D_FW signify Fischer Tropsch diesel obtained from straw and forest wood, respectively

4 Future Scenarios

For future scenarios of the deployment of FT-Diesel from wheat straw and pine forest residue pellets via Chemical Looping Gasification (CLG), overall production cost and CO_2 price/environmental performance scenarios for the years 2030 and 2050 have been considered and can be seen in **Figure 4** and **5**, respectively. In a second step, the Technological Learning (TL) Curve for Chemical Looping Gasification has been considered in order to draw inferences with regards of the expected Technological Readiness of CLG in the coming years and its implications on future FT-Diesel deployment.

4.1 CO_2 & Overall Production Price Development Scenarios

Figure 4 depicts the total production cost structure scenarios for 2030 and 2050, calculated and compares these with the corresponding forecasts of total production costs of diesel (€/kWh). It is evident that already in 2030 the production of FT diesel could be economically feasible and lower than that of conventional diesel, given our assumption that CO_2 taxes of ~180 €/ t CO_2 are going to be implemented. In 2050, both production costs as well as CO_2 taxes on conventional diesel are expected to increase, accompanied by a further decline of both costs for FT Diesel, thus rendering FT diesel a valuable alternative, both economically and environmentally.

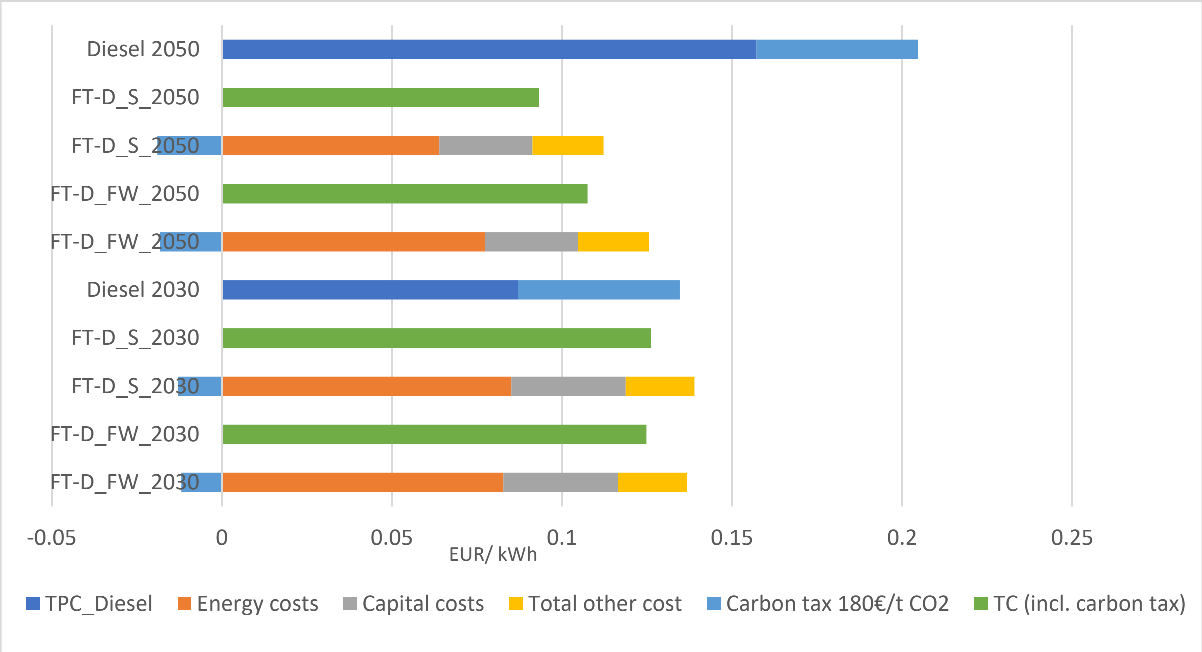

Figure 4: Segmented total production costs scenarios for forest wood-to-FT diesel & straw-to-FT diesel chains incl. CO_2 taxes for 2030 and 2050 compared to corresponding Diesel prices (EUR/kWh) for the EU

An environmental assessment in terms of CO_2 balances for wheat straw pellets and pine forest residue to FT Diesel have been carried for the base year of 2020 and subsequently has been compared to scenarios for 2030 and 2050, as well as to corresponding conventional diesel CO_2 balances, as can be seen in **Figure 4**. The blue bars represent the CO_2 emissions expected due to the growing and harvesting of biomass, while the orange bars represent the CO_2 emissions expected due to the FT-Diesel (fuel) production (i.e. the gasification of biomass, the transportation of crude to refinery etc.). The grey bars denote the overall CO_2 emissions expected per chain and year, e.g. the overall CO_2 emissions for the production of FT Diesel from forest wood in 2020 has been calculated to be ~1,25 kg CO_2/ kg fuel, while for the same chain constellation in the year 2030 it is expected to drop to 0,5 kg CO_2/ kg fuel. The inferior environmental performance of conventional Diesel is evident with an overall CO2 balance of ~ 3,25 kg CO_2/ kg fuel. While it is evident that, at present, the ecologic performance of FT diesel is already superior to that of conventional diesel, the environmental benefits in terms of negative lifecycle carbon emissions (kg CO_2/kg fuel) are expected to continuously increase until 2050 for both biomass-to- FT diesel chains under study.

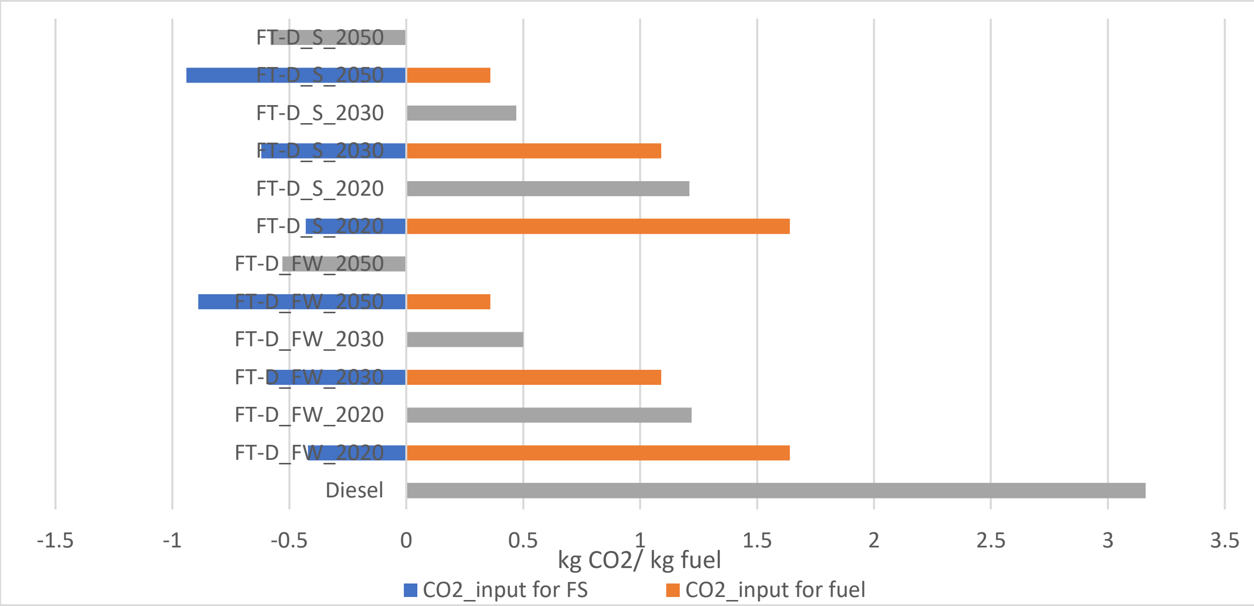

Figure 5: CO_2 balances for forest wood-to-FT diesel & straw-to-FT diesel chains for 2020, 2030 and 2050 compared to corresponding Diesel CO2 (TTW emissions) for the EU[5]

4.2 Technological Learning & Scenarios

In order to further assess the perspective for the economics of Chemical Looping Gasification (CLG) up to 2050, technological learning was modelled by using learning rates. Equation (3) is used to describe an experience curve:

$$IC_{New}(x_t) = IC(x_{t_0}) \cdot (\frac{x_t}{x_{t_0}})^{-b}$$

where IC_{New} represents the cost for the investment in the new parts of the technology at t, b is the learning index, while IC_0 states the investments at t_0. Finally, x is the amount manufactured cumulative until time t respectively t_0 for a single Chemical Looping Gasification (CLG) Plant at t. **Figure 6** depicts four scenarios developed for the investment expenses of CLG plants based on expected advances in CLG technology (technological learning), using specific learning rates of 15% and 25% and assumed growth factors of 2,00 and 2,50. All of the technological learning scenarios depicted were developed for a 200 MWth CLG plant, assuming a total investment

[5] Where FT-D_S and FT-D_FW signify Fischer Tropsch diesel obtained from straw and forest wood, respectively and FS denotes Feedstock (Biomass)

cost of 272,96 Mio. € (as estimated previously in Task 7.2) and as a starting point one already operating plant was currently assumed (although this technology is currently still in the pilot phase, a successful operation of at least one plant at 200 MW_{th} in the foreseeable future was deemed a justified assumption).

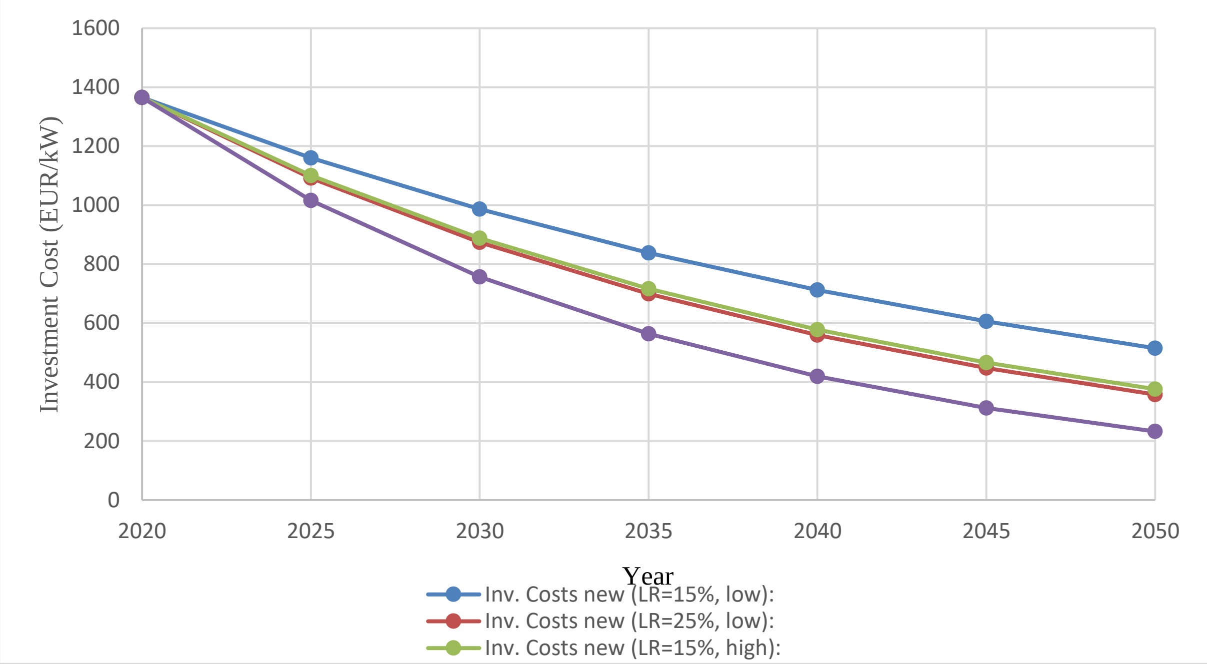

Figure 6: Future prospects for investment costs of CLG plants with learning rates of 15% & 25%

Figure 6 depicts the four previously mentioned scenarios for CLG investment costs, namely:

- Scenario 1: Learning rate of 15%, growth factor of 2,00 (*low*)
- Scenario 2: Learning rate of 15%, growth factor of 2,5 (*high*)
- Scenario 3: Learning rate of 25%, growth factor of 2,00 (*low*)
- Scenario 4: Learning rate of 25%, growth factor of 2,5 (*high*)

Overall, the learning curve analysis that was carried out suggests that the total investment costs for a CLG plant are expected to continuously drop until 2050, across all four scenarios. The highest drop in investment costs is expected to occur with Scenario 4, in which both a maximum learning rate of 25% and a high growth factor of 2,5 is assumed – which translates into a steep and continuous advancement of the CLG technology over the years and a rapid rise in the overall number of CLG plants worldwide. In the case of scenario 4, a drop of investment costs from ~1400 €/kW to ~ 750 €/kW by 2030 and ~230 €/kW by 2050 is expected. In contrast, when assuming a learning rate of 15% and a lower growth factor of 2,00, then the investment costs are expected to drop to ~980 €/kW by 2030 and to ~510 €/kW by 2050.

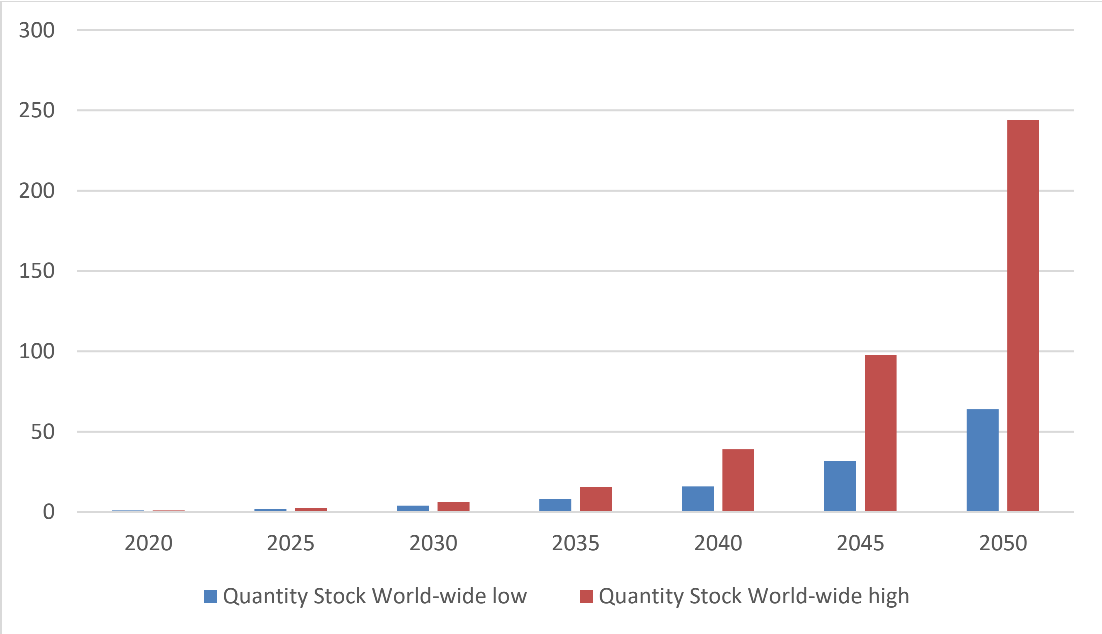

Figure 7: Projected quantity of CLG plants worldwide for growth rates 2,00 & 2,50 until 2050

Figure 7 depicts the projected quantity of CLG plants worldwide for low (2,00) and high (2,50) growth rates: while the high growth rate scenario projects almost 250 CLG plants worldwide, the low growth rate scenario projects ~65 CLG plants. In either scenario a significant and continuous decrease in overall investment costs for CLG plants is expected. It is expected that the number of CLG plants is directly proportional with desirable social benefits, such as the creation of local jobs and an increase of the overall affluence and educational level of local communities.

An area of further research to complement this study would be to compare the Technological Learning Curves of various technologies to Chemical Looping Gasification (CLG), e.g. Dual Fluidized Bed Gasification (DFBG).

5 Recommendations & Conclusions

The major conclusions of this analysis are:

(i) The way towards an increased share of 2nd generation biofuels, such as FT diesel, in the overall energy mix has to be accompanied by rigorous policy measures (e.g. regulations for min. share of renewable fuels in total energy mix);

(ii) In order for 2nd generation biofuels to play a significant role in the energy transition, a proper mix of CO_2-taxes and intensified R&D in order to improve the conversion efficiency from feedstock to fuel, thus leading to lower feedstock cost and improved ecological performance, are needed

(iii) The increase in production price and CO_2 taxes of conventional diesel, combined with the increase in ecologic and economic performance of 2nd generation biofuels, such as FT diesel, is highly likely to cause the latter to supersede conventional diesel by 2030, if not earlier.

In addition to the above, it should be pointed out that recent data on the feedstock costs for both straw and forest residues from the CLARA project suggested that these are significantly lower (36 €/ ton wheat straw & 50 €/ ton pine forest residue) than e.g. the estimate by Ajanovic et al. 2012 (119 €/ ton for straw & 129 €/ ton forest wood) for the year 2020. The cost of feedstock (€/ton) has a significant and determinative effect on the overall costs of the full biomass-to FT diesel chain and the lower than expected feedstock prices combined with CO_2 taxes could lead to FT diesel production from wheat straw being economically feasible earlier than expected and approximately equal to conventional diesel in 2020, as is visualized in **Figure 8** below.

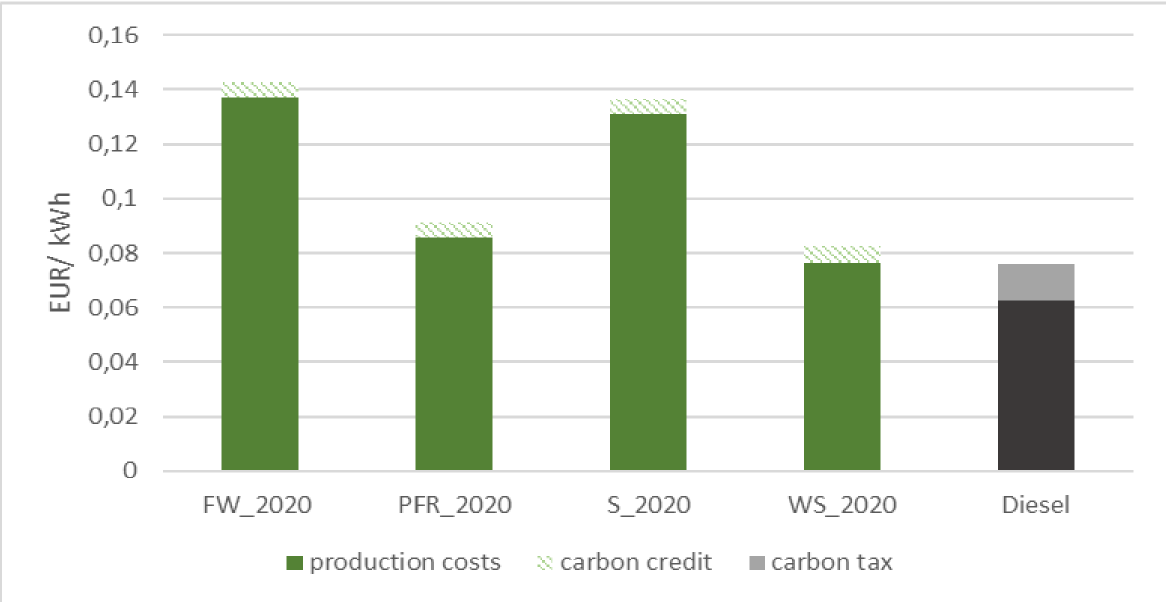

Figure 8: Total production cost scenarios for forest wood-to-FT diesel, pine forest residue-to-FT diesel, straw-to-FT diesel and wheat straw-to-FT diesel chains incl. CO_2 taxes for 2020 (based on literature & data from CLARA project) compared to corresponding Diesel prices (EUR/kWh) for EU[6]

FT- Diesel production being forecasted to become economically feasible by the mid-2020s, paired with its environmental benignity render it a valuable alternative to fossil fuels. Furthermore, the expected steep technological learning effects, resulting in lower overall investment costs for CLG plants, warrant a financially and ecologically successful and

[6] Where FW signifies forest wood and S signifies straw (feedstock prices as previously forecasted for 2020, byAjanovic et al.) and PFR signifies pine forest resides and WS wheat straw (feedstock prices as reported by CLARA project)

continuously increasing deployment of FT-Diesel. It is expected that the deployment of FT Diesel and thus an increase of CLG plants is directly proportional with desirable social benefits, such as the creation of local jobs and an increase of the overall affluence and educational level of local communities.

6 Disclaimer

The content of this deliverable reflects only the author's view, and the European Commission is not responsible for any use that may be made of the information it contains.

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